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HAC REF J4924

AFOSR-TR- 94 0311

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PASOTRON TECHNOLOGY

AD-A279 994

J. M. Butler, D. M. Goebel, and J. Santoru

Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, California 90265

R. L. Eisenhart

Hughes Missile System Company
8236 Fallbrook Avenue
Canoga Park, California

January 1994

Final
[redacted]l Contract Report

Contract F49620-92-C-0015

January 1, 1993 through December 31, 1993

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Bolling Air force Base
Washington, DC 20332-6448

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
94/2/1

3. REPORT TYPE AND DATES COVERED
[redacted] Report Final
January 1,1993 through December 31, 1993

4. TITLE AND SUBTITLE
PASOTRON TECHNOLOGY

5. FUNDING NUMBERS
2301 ES

6. AUTHOR(S)
J.M. Butler, D.M. Goebel, and J. Santoru

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

8. PERFORMING ORGANIZATION REPORT NUMBER
J4924
AFOSR-TR- 94 0311

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
Building 410
Bolling AFB, DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-92-C-0015

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

This annual report describes research progress made in the second year of the PASOTRON Technology Program. This program is a two year effort sponsored by the Air Force Office of Scientific Research to develop and investigate a single-stage amplifier and a multi-stage oscillator; each based on Hughes' Plasma-Assisted, Slow-Wave Oscillator (PASOTRON™) technology. During the program's second year amplifier performance was briefly re-explored to take advantage of system and diagnostic upgrades implemented by HRL under a parallel IR&D Program; and the first stage of the multi-stage oscillator was demonstrated. Data is reported showing improved amplifier performance. Amplifier gains of 10-to-17 dB were maintained; while instantaneous bandwidth was increased from 0.1% to 1.0%. Amplified power levels of several tens to hundred kilowatts were measured to give a factor-of-ten increase in efficiency to levels of a few present. The first phase measurements were completed, and coherent amplifier operation was achieved with phase stability of up to 0.005 deg/V. Additionally, a multi-stage oscillator system was designed and experimental investigations were conducted on the first stage of the three-stage apparatus. Characterization of the second and third stages will be completed during the program's three-month no-cost extension.

14. SUBJECT TERMS

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Introduction

The PASOTRON Technology Program is a two year effort sponsored by the Air Force Office of Scientific Research to develop and investigate a single-stage amplifier and a multi-stage oscillator; each based on Hughes' Plasma-Assisted, Slow-Wave Oscillator (PASOTRON^{TM}) technology. The focus of this research is to investigate the fundamental operation of PASOTRON devices, evaluate linear and non-linear operation by correlating results with existing theories and numerical calculations, and assess behavior unique to the PASOTRON's use of non-magnetically confined beam transport. Results from this work will advance our understanding of the fundamental microwave generation process of both vacuum and plasma-assisted, slow-wave devices. This increased understanding of high-power-microwave source operation will enable high-energy RF systems which provide reliable phase and frequency controlled outputs will enable the upgrade of Electronic-Warfare (EW) and High-Power-Counter-Measure (HPCM) systems.

Research conducted during the program's first year concentrated on the demonstration of a single-stage amplifier and the characterization of the source's performance. These investigations were unfortunately limited by the klystron which was available for use as the RF drive source. During the program's second year, amplifier performance was briefly re-explored to take advantage of system and diagnostic upgrades implemented by HRL under a parallel Independent Research and Development (IR&D) Program. Two Slow-Wave Structure (SWS) lengths were re-investigated; improved amplifier performance was achieved, and phase measurements demonstrated stable-amplifier operation. As scheduled, the multi-stage oscillator system was designed and experimental investigations were conducted on the first of the three stage apparatus. Characterization of the second and third stages will be completed during the program's three-month no-cost extension. This annual report briefly overviews research progress made in the program's second year and includes a copy of 1993's ICOPS presentation.

Amplifier Progress

During the program's first year, a PASOTRON amplifier was demonstrated and characterized. Amplifier gain, peak power, efficiency, and instantaneous bandwidth were measured as a function of X-band drive frequency, beam voltage and current, background gas pressure, and structure length. Overall results from these experimental investigations are shown in Table 1.0 and compared to our design goals. Poor amplifier performance was attributed to RF drive source limitations and a structure design which forced operation near the TM_{01} amplifier mode's upper cut-off frequency range.

Table 1.0 PASOTRON Amplifier goals and demonstrated parameters.

Parameter	Goals	Demonstrated
RF Drive Source		Klystron
Center Frequency	10 GHz	10.12 GHz
Bandwidth	1000 MHz	40 MHz
Peak Power	10-to-100 kW	2.7 kW
Pulsewidth	120 µsec-to-CW	120 µSec
PASOTRON Amplifier		
Beam Voltage	50-to-100 kV	50-to-100 kV
Beam Current	50-to-150 A	80-to-120 A
Gain	10-to-30 dB	17 dB
Power	1-to-5 MW	7 kW
Efficiency	15-to-30%	0.1%
Bandwidth	10%	0.1%
Pulsewidth	100 µSec	80 µsec
Phase	0.01deg/V	NA

To increase RF-power-handling capability and instantaneous bandwidth, the X-band PASOTRON amplifier was upgraded in 1993 under HRL's IR&D Program. To improve the ability to extract and direct amplified radiation, a new side-wall RF extractor was fabricated and integrated into the laboratory apparatus downstream of the amplifier. The original PASOTRON amplifier configuration is shown in Fig. 1; and the upgraded system is shown in Fig. 2. The downstream RF extractor is a four-port-coupler similar to the RF injection section positioned upstream of the amplifier. This downstream coupler efficiently extracts and converts the amplified RF power in a TM_{01} cylindrical waveguide mode into a TE_{10} rectangular waveguide mode. In this configuration, the high-power amplifier output is contained in waveguide, easily monitored using standard waveguide couplers, and guided to radiating elements or terminated in a high-power load.

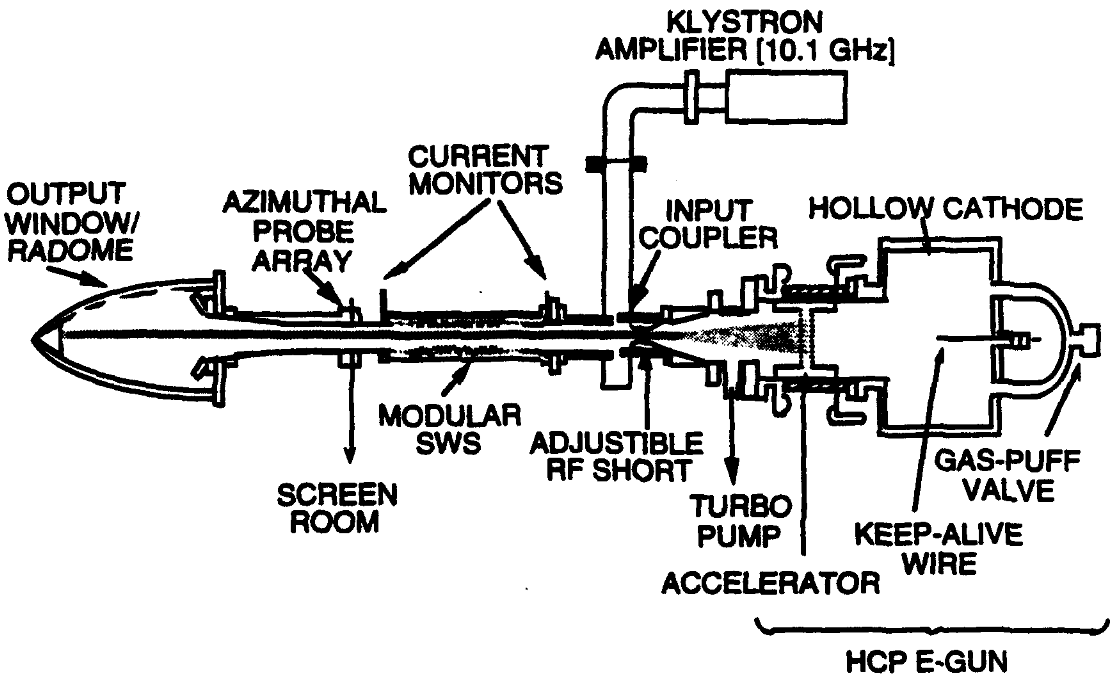


Figure 1. Schematic Diagram of first X-band PASOTRON Amplifier Apparatus.

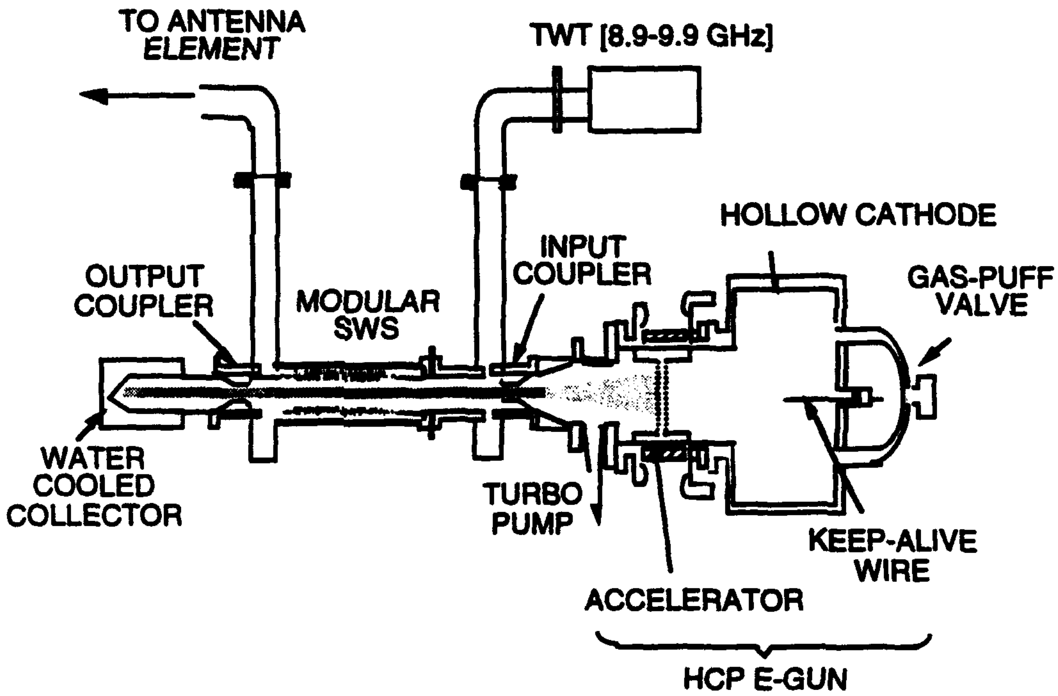
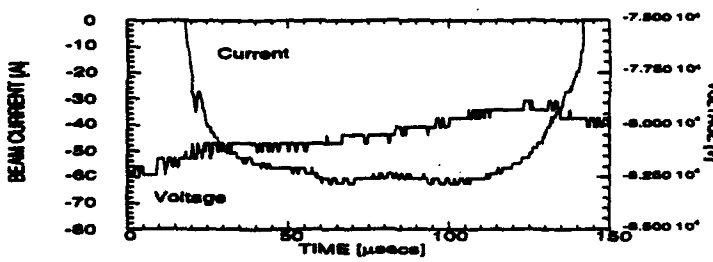


Figure 2. Schematic Diagram of upgrade X-band PASOTRON Amplifier Apparatus.

The RF drive system was upgraded with a new Hughes' 8713H TWT to provide a 3-to-8-kW-peak, 100-μsec-long signal to an amplifier over a tunable frequency range of 8.9-to-9.9 GHz. The system's diagnostic capabilities were improved through the development of phase discrimination circuitry. The phase relationship between the input RF signal and the amplifier output RF signal was determined with an ANAREN 20578 series phase discriminator. The phase discriminator response for a typical test shot is shown in Fig. 3; as well as the beam current, beam voltage, and calibrated microwave detector outputs. These traces show an amplifier phase stability of 0.02 deg/V. This demonstration of phase-stable operation will enable future development of electronically-controlled-phase-array systems.

a)



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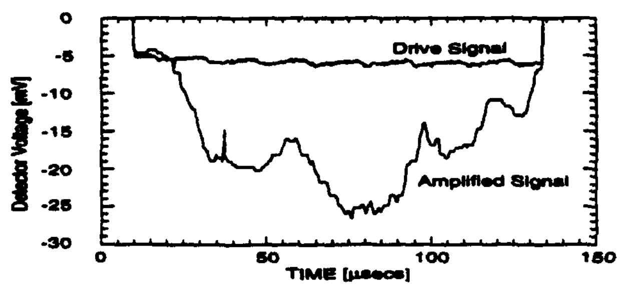

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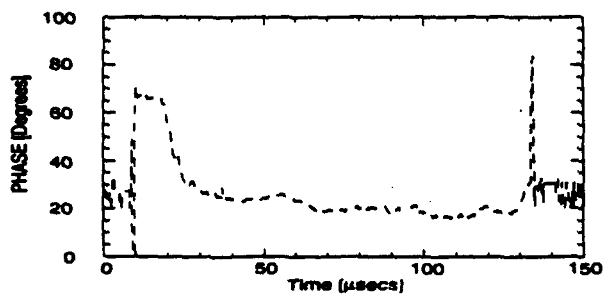


Figure 3. Oscilloscope traces showing a)beam current and voltage, b) calibrated RF detectors monitoring amplifier input and output, and c) Phase angle.

During the second year of the PASOTRON Technology Program, the upgraded amplifier system was re-explored at two structure lengths. As a result of these unscheduled amplifier investigations, greatly improved amplifier performance was achieved as shown in Table 2. Amplifier gains of 10-to-17 dB were maintained; while instantaneous bandwidth was increased from 0.1% to 1.0%. Amplified power levels of several tens of kilowatts were measured to give a factor-of-ten increase in efficiency to levels of a few present. The first phase measurements were completed, and coherent amplifier operation was achieved with phase stability of up to 0.005 deg/V.

Table 2. PASOTRON Amplifier Goals and demonstrated specifications

Parameter	Goals	Demonstrated	Demonstrated
RF Drive Source		Klystron	TWT
Center Frequency	10 GHz	10.12 GHz	9.5 GHz
Bandwidth	1000 MHz	40 MHz	1000 MHz
Peak Power	10-to-100 kW	2.7 kW	8.2 kW
Pulsewidth	120 μsec-to-CW	120 μSec	120 μSec
PASOTRON			
Beam Voltage	50-100 kV	50-100 kV	50-100 kV
Beam Current	50-150 A	80-120 A	80-120 A
Gain	10-30 dB	0-17 dB	0-17 dB
Power	1-to-5 MW	7 kW	100 kW
Efficiency	15-to-30 %	0.1%	3.0 %
Bandwidth	10 %	0.1 %	1.0 %
Pulsewidth	100 μSec	80 μsec	80 μsec
Phase	0.01deg/V	NA	0.005deg/V

Multi-Stage Oscillator Progress

During oscillator operation, electron-beam energy is transferred to electromagnetic wave fields in a direction anti-parallel to beam propagation. The multi-stage oscillator concept uses multiple outlet ports to extract RF power at several intervals along the SWS's axial length. This configuration eliminates signal reflections which adversely influence the RF generating instability such as frequency pulling, and reduces signal attenuation which occurs in most BWOs as the RF signal is reflected upstream and redirected downstream for extraction.

In the PASOTRON Technology Program's second year the multi-stage oscillator was designed and the first of the three stages was investigated. As shown in the schematic of Fig. 4, RF power is coupled out upstream of the SWS's interaction region. This is achieved via a series of four-port couplers which extract the oscillators TM_{01} mode radiation and convert it into rectangular TE_{10} mode. The couplers are similar in design to those employed in the amplifier apparatus.

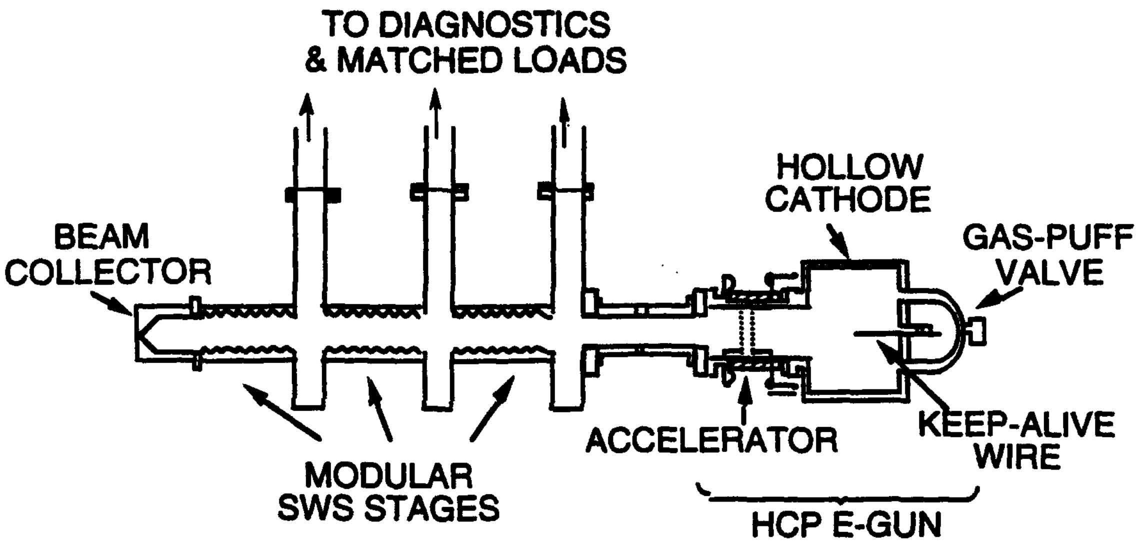


Figure 4. Schematic diagram of Multi-Stage PASOTRON apparatus.

The SWS is designed to operate as an X-band oscillator for beam voltages ranging from 50-to-100 kV. A cold-SWS dispersion diagram is presented in Fig. 4. The structure has an average radius of 2.54 cm, a ripple period of 1.2 cm, and ripple depth of 0.254 cm. To enable characterization of the oscillator's performance as a function of structure length, the SWS was fabricated using the modular approach previously implemented in the amplifier investigations. This basic modular design is shown in Fig. 6.

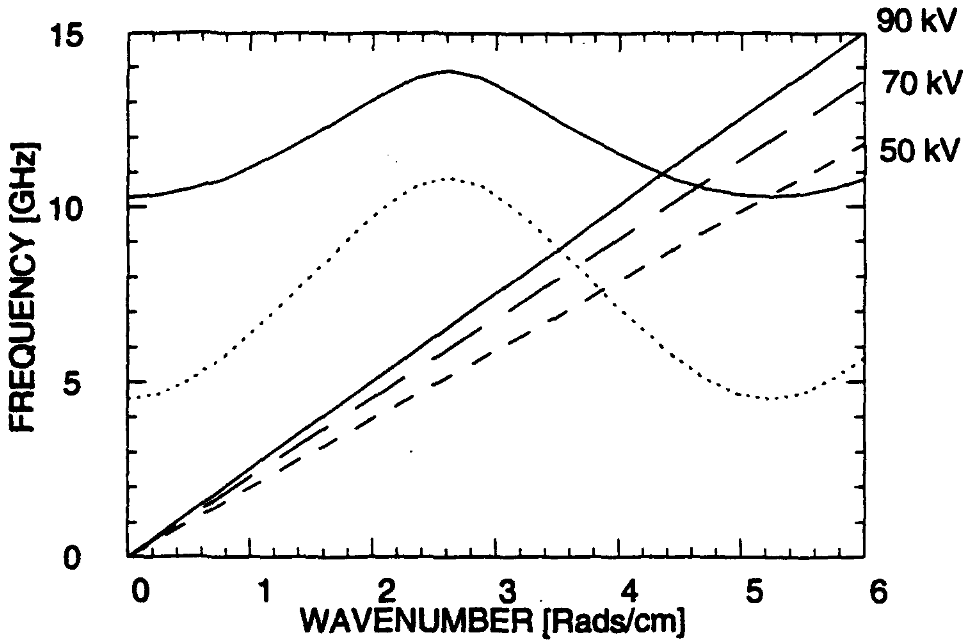


Figure 5. Cold dispersion diagram of the Multi-Stage PASOTRON Oscillator's SWS.

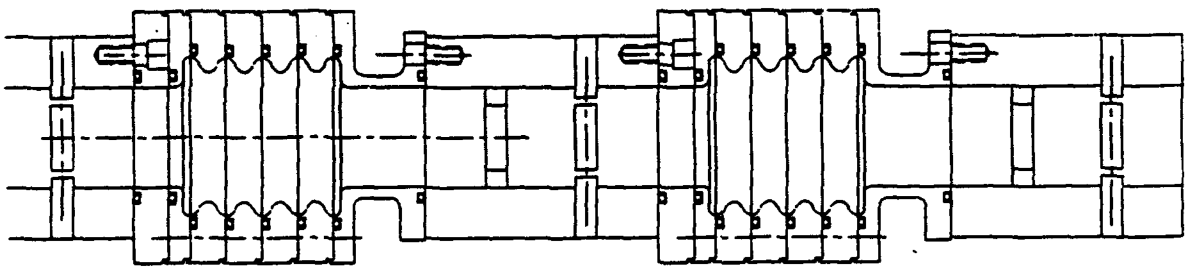


Fig.6 Diagram of modular multi-stage oscillator construction.

A series of preliminary investigations were completed to study the single-stage oscillator's performance and implement system upgrades as needed. These experiments indicated that propagation of the high-current beam was being adversely effected by the extractors which are equipped with frequency-cutoffs consisting of small-diameter waveguide sections. This was not a significant issue in the previous amplifier experiments since low-beam current was desired and beam scrap off on this sections was tolerable. However, in the oscillator larger currents are required to meet start oscillation conditions of the SWS. Thus, to improve beam transport efficiency, the RF extractors were redesigned to provided an increased diameter. Testing of the upgraded system is underway.

Research Plan

During the three-month program extension, multi-stage oscillator performance will be characterized as a function of SWS length and number of stages. RF properties of power, pulsewidth, frequency, and efficiency of a single-stage will be measured as a function of beam voltage, beam current, and SWS length. Following single-stage investigations, a second RF extractor will be positioned in the midst of the SWS. The two-stage oscillator's RF properties will again be characterized including the phase stability between the two outputs. This procedure will be repeated for the three-stage system. Experimental results and analyses from these investigations and all previous amplifier research will be correlated and presented in the final report.

PASOTRON Amplifier Experiments

Jennifer M. Butler, Dan M. Goebel, and Paul W. Sumner
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265
(310)317-5372

Robert L. Eisenhart
Hughes Missile System Company
Canoga Park, CA

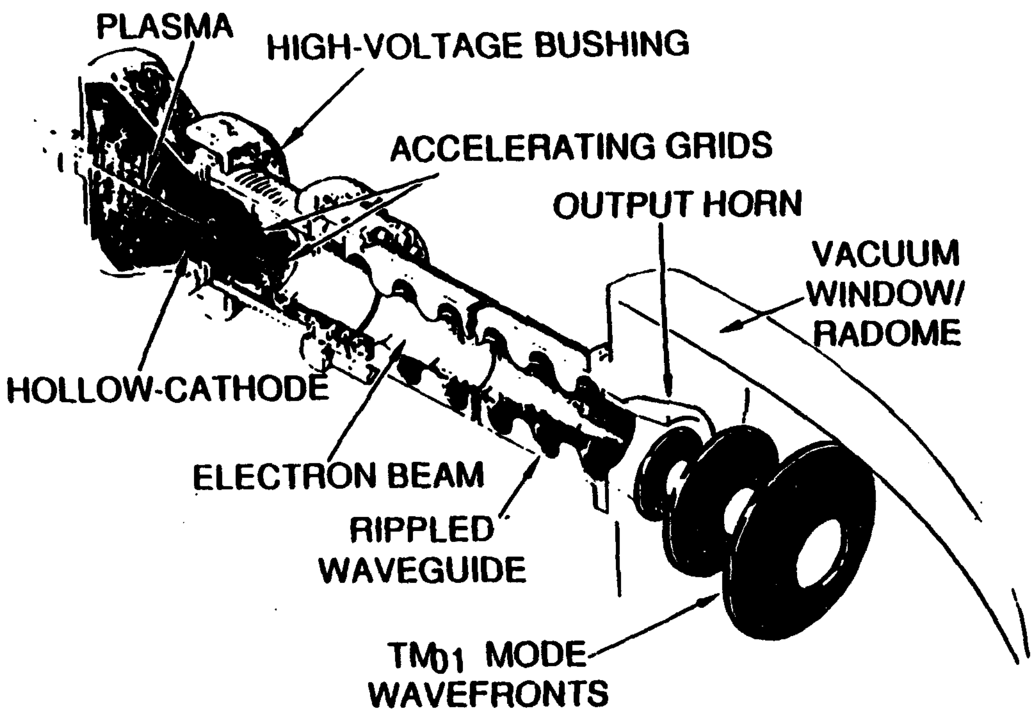
7 June 1993

HUGHES

HUGHES PASOTRON
High Power Microwave Source

HUGHES
RESEARCH LABORATORIES

9212-13-003



PLASMA ASSISTED SLOW-WAVE OSCILLATOR
- Compact, lightweight, unmagnetized BWO
- High average-power, deployable HPM source

PERFORMANCE

Simultaneous Parameters

Peak Power	1 - 5 MW
Pulse Length	100 µsec
Voltage	≤100 kV
Efficiency	≈20%
PRF(gas puff)	≤ 1 Hz
Frequency	C-Band
Linewidth	<10 MHz

Demonstrated Capabilities

Frequencies L, S, X-Band
PRF (static gas) 1 kHz
Amplifier Operation

Predicted Features

Tuneability	≥10%
Duty	>10%
High Average Power	

Hughes Research Laboratories
Dr. Jennifer Butler
(310) 317-5372

PASOTRON Technology

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PASOTRON systems are high-energy microwave sources which utilize a novel hollow-cathode-plasma, electron-gun, and plasma-filled, slow-wave structure (SWS) to efficiently convert 100-μsec long, 50-to-100 kV, 50-to-250 A electron-beam pulses into long, high-energy rf pulses. The devices are operated in the ion focused regime thus no axial magnetic fields are required for beam transport through the SWS. Through the use of geometrically different SWS's, operation of the PASOTRON has been demonstrated as an oscillator in S, C, X, and Ku-bands, and as an amplifier in X-band.

The Electron Gun

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Long electron-beam pulses at high-current density are obtained by using a stabilized **<u>Hollow-Cathode Plasma (HCP) Electron gun</u>**. This gun overcomes the limitations of most high-power microwave tubes which employ either thermionic cathodes that have limited current density (<5 A/cm^2) or field emission cathodes that offer high-current density, but suffer from short pulsewidth capability (<< 1 µsec) because of plasma closure of the accelerating gap.

The HCP electron gun provides both high-current density (100 A/cm^2) and long-pulse operation without gap closure by using a low-pressure glow discharge inside a hollow cathode.The plasma density is controlled by a low-voltage HC-discharge pulser to provide space charge limited emission of electrons. A dc high-voltage electron-beam supply accelerates electrons across the A-K gap while the HC pulser modulates the beam current to generate arbitrary pulse waveforms.

The Hollow-Cathode Plasma (HCP) Electron-Gun

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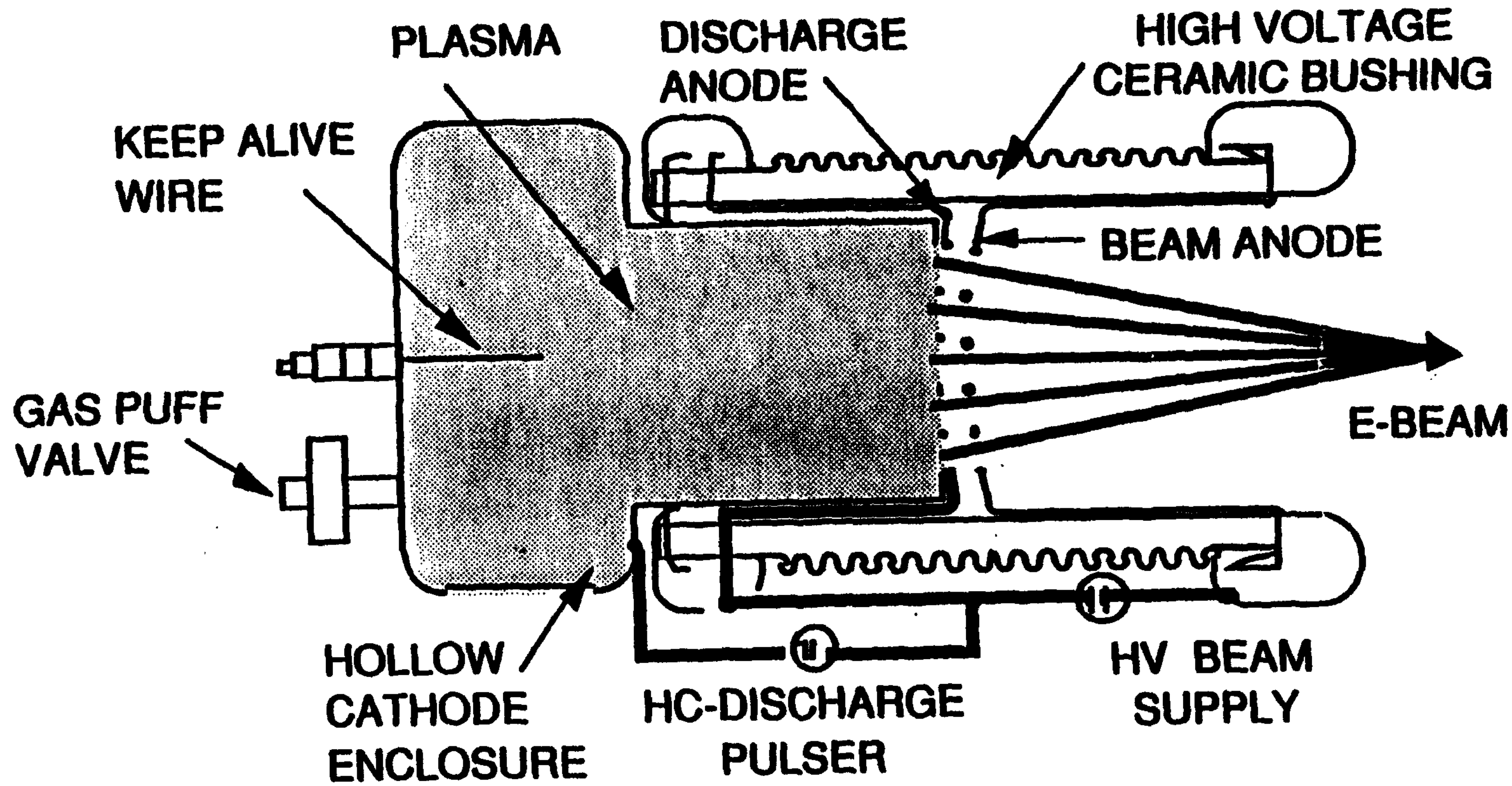

Features

- High-Current Density (<100 A/CM^2)
- Stable Plasma Front
- Long-Pulse Operation Without Closure
- No Heater Power

*HUGHES-PATENTED TECHNOLOGY
-PATENT NO. 3,831,052
-PATENT NO. 3,949260

HCP E-Gun Performance

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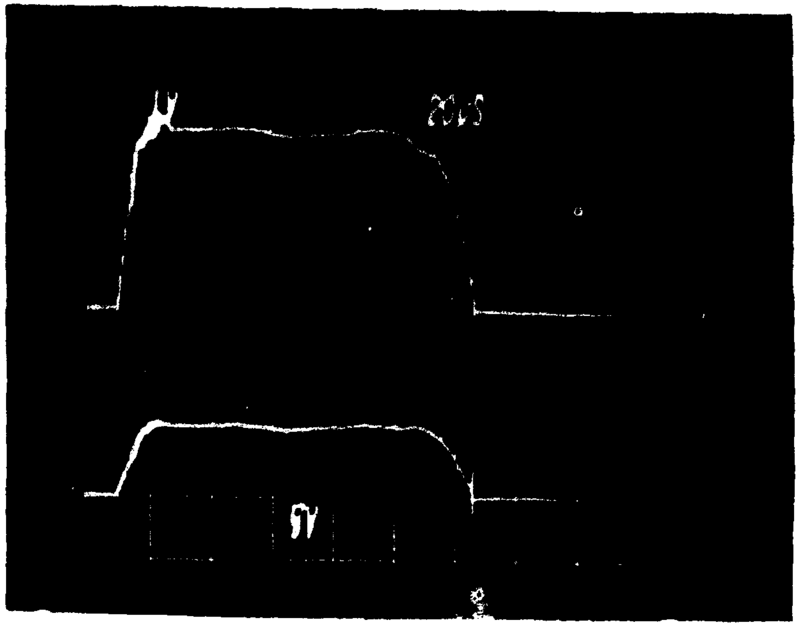
Beam Current
(100A/div)

HC Discharge
Current
(500A/div)



20 μSec/div

Beam Voltage: 95 kV
Beam Current: 300 A
PulseWidth: 100 μsec

Ion-Focused Electron Beam transport

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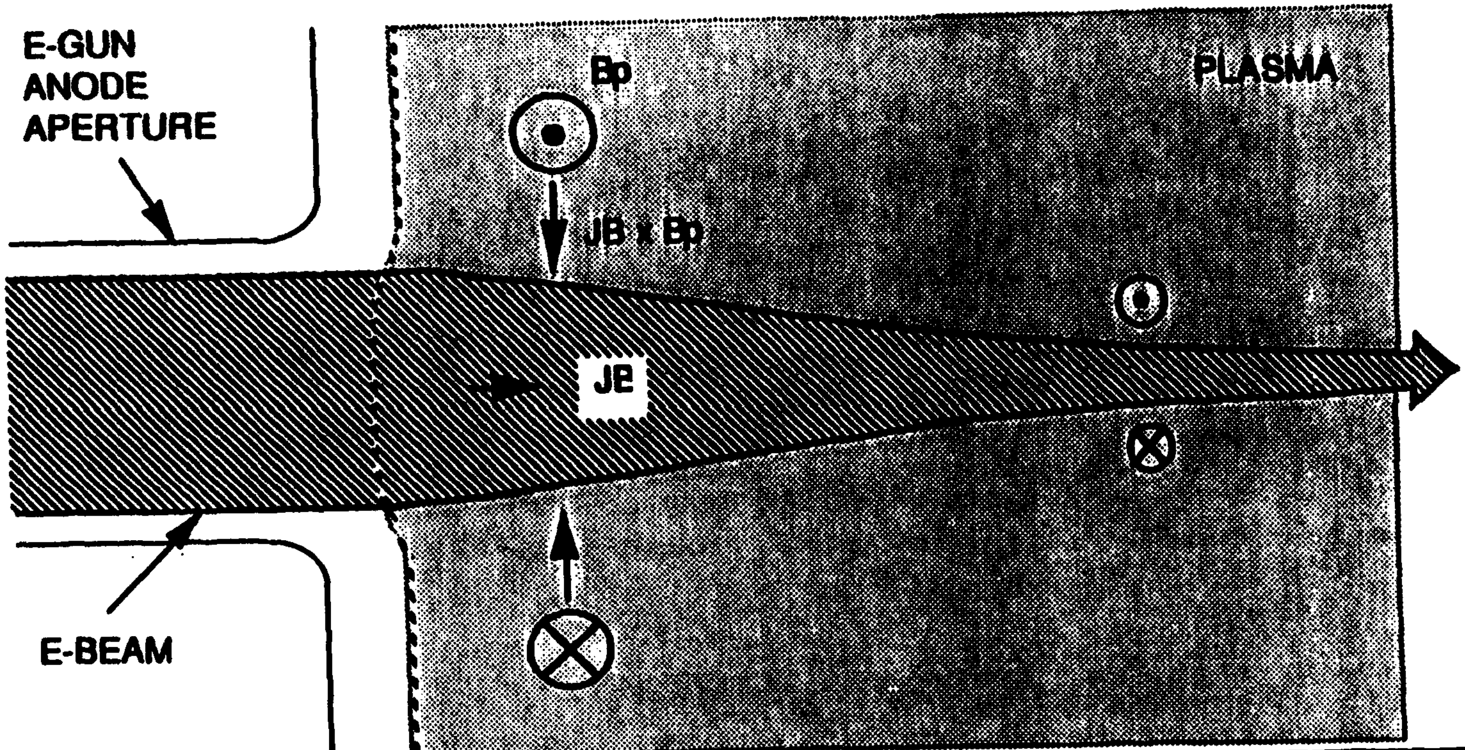

Radial space-charge forces responsible for beam expansion are eliminated by allowing the beam to ionize a low-pressure gas. In the absence of space-charge forces and an exter[illegible]l magnetic field, the beam's self-magnetic field can cause the beam radius to compress. This process, graphically represented Above is commonly known as the Bennett Pinch Effect

RF Generation

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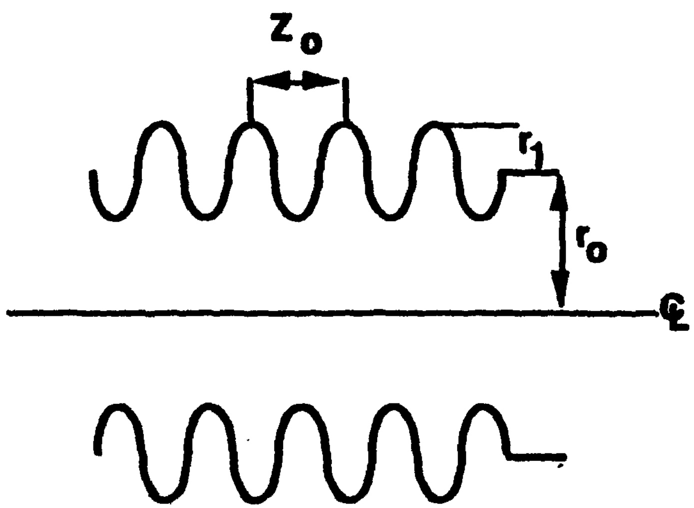
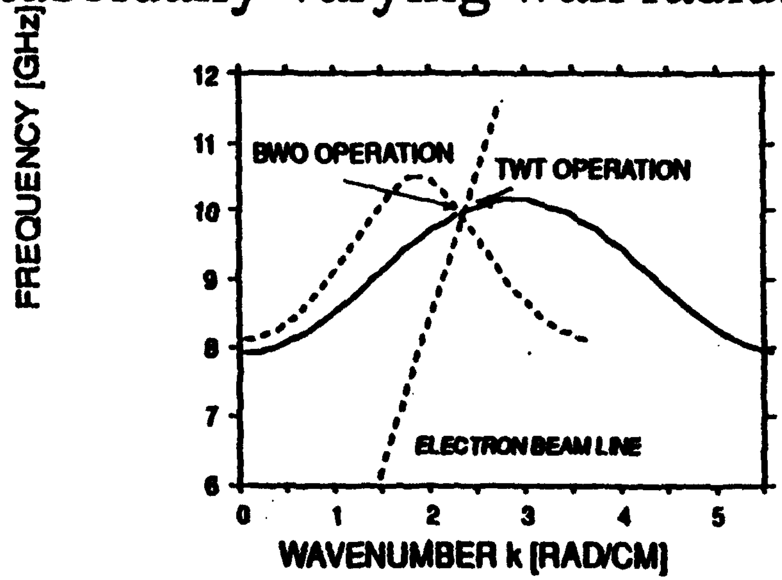
The compressed electron beam enters a SWS composed of a hollow-cylindrical-waveguide with a sinusoidally-varying wall radius.





As the beam propagates through the SWS, resonances can occur between the beam's slow space charge wave and SWS's slow EM waves. When both waves have matching phase velocity, resonant interactions are possible during which e-beam energy can be transferred to the EM fields resulting in the spontaneous generation (BWO operation) or amplification (TWT operation) of RF radiation.

Amplifier Design Goals

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Electron Beam Generator (Available)

Beam Voltage	50-to-100 kV
Beam Current	50-to-600 A
Beam Diameter	2 cm
Pulsewidth	50-to-125 μSecs
PRF	1 Hz

RF Drive Sources:	Varian Klystron(Available)	Hughes TWT (Upgrade)
Center Frequency	10.12 GHz	9.45 GHz
Tuneable Bandwidth(+/-)	15 MHz	500 MHz
Peak Power	2.5 kW	10 kW
Pulsewidth	100 μsec	100 μsec

Amplifier (SWS Design Based on Klystron)

Center Frequency	10.0 GHz (X-band)
Bandwidth	10 %
Gain	10-to-30 dB
Peak Power	0.01-to-1.0 MW
Efficiency	10-to-25 %
Pulsewidth	100 μsecs

Experimental Amplifier Apparatus Schematic

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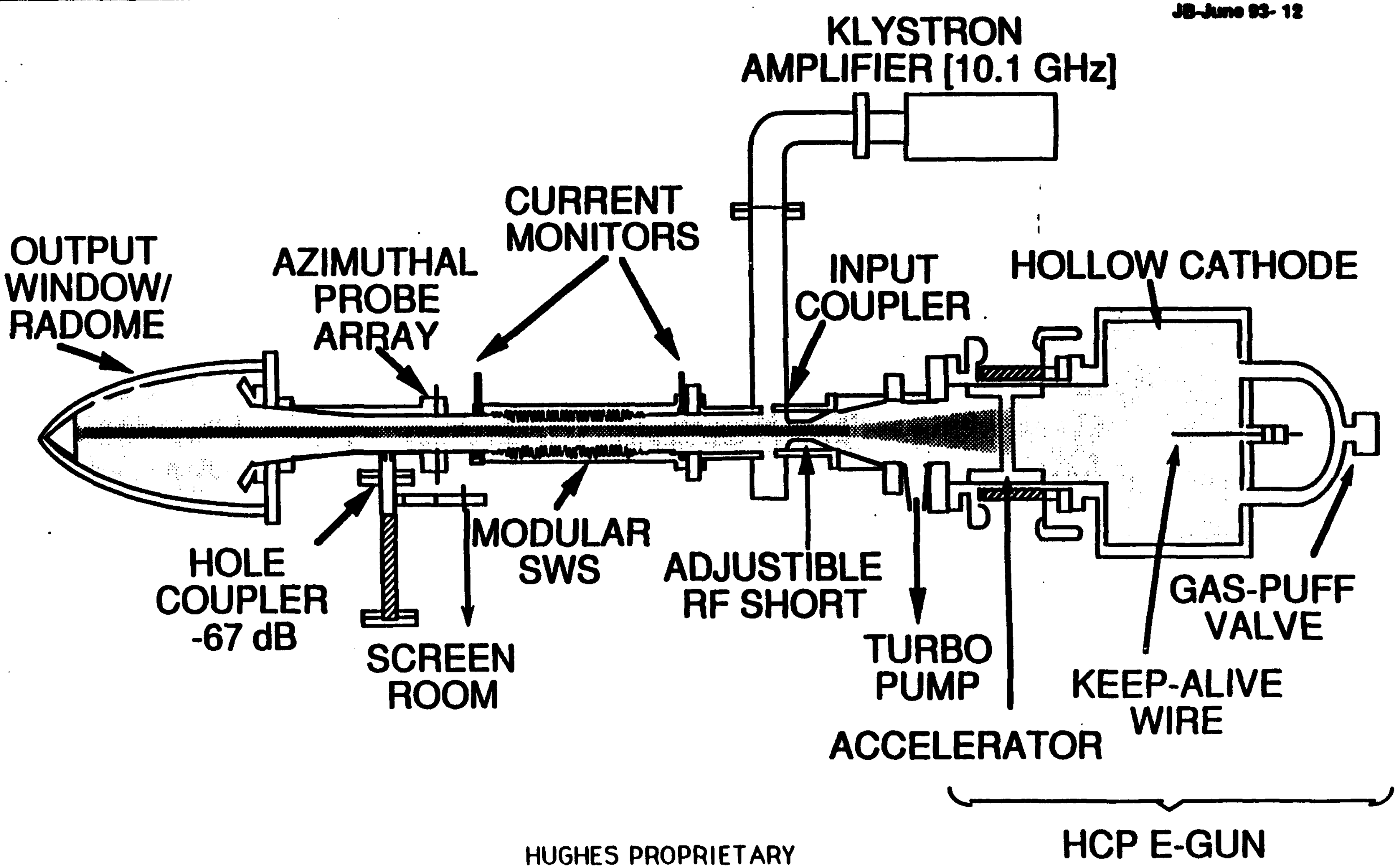

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Analytical SWS Design

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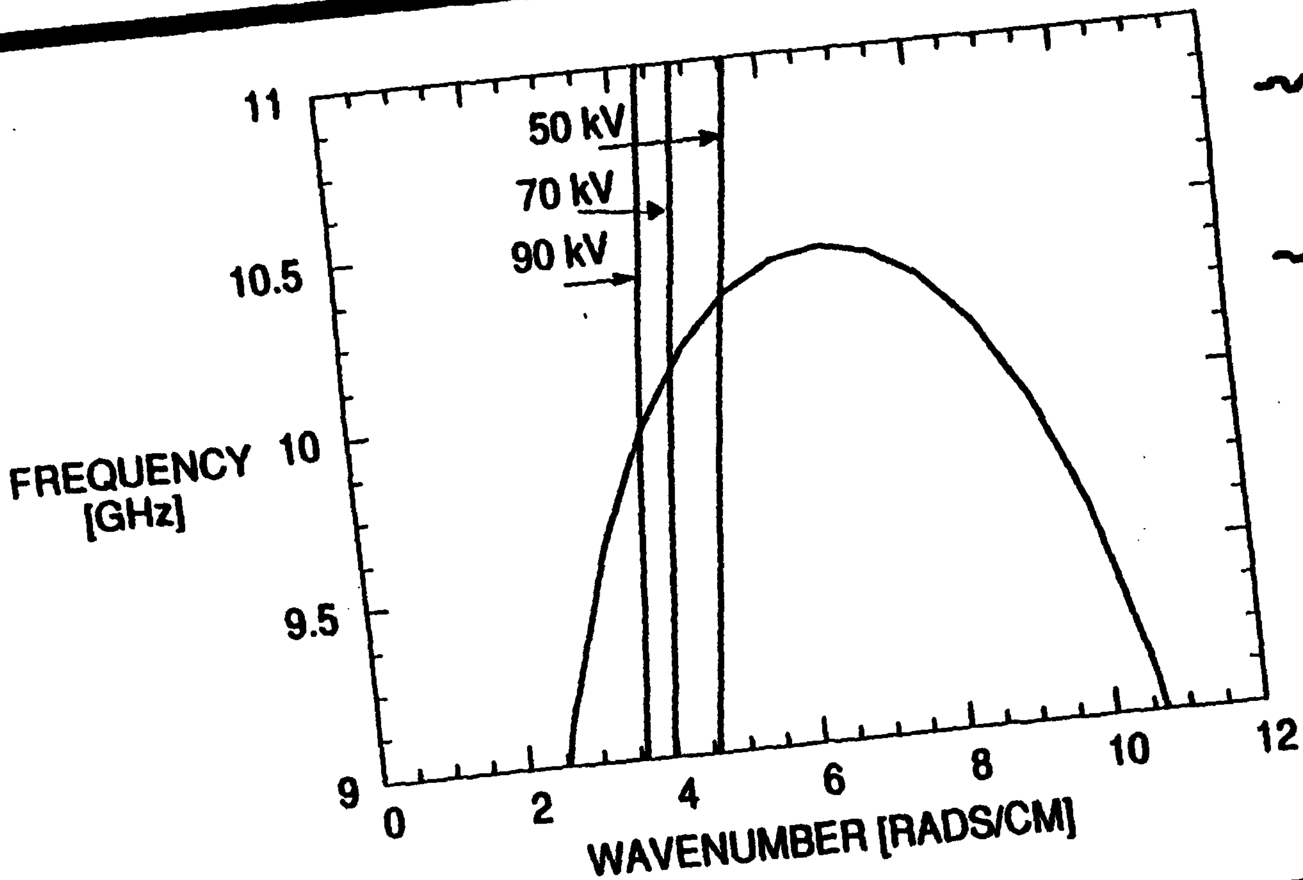

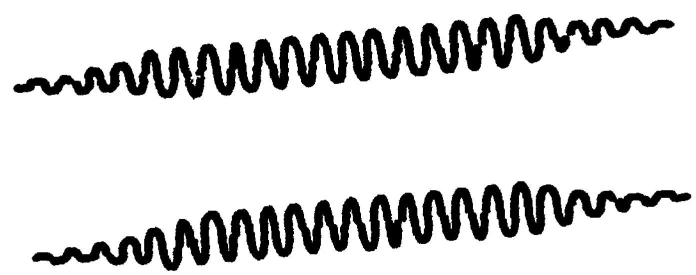

SWS Geometry
Ro=1.75 cm
R1=.5 cm
Zo=.48
Eps=28.5%
#periods=5-to-45

Design Requirements
- Forward Wave Interaction
- Resonant Frequency Compatible with RF Drive Source
- Flexible SWS Construction to Enable Length Variation
- Input and Output Tapers to Avoid Feedback

Input RF Launcher Performance

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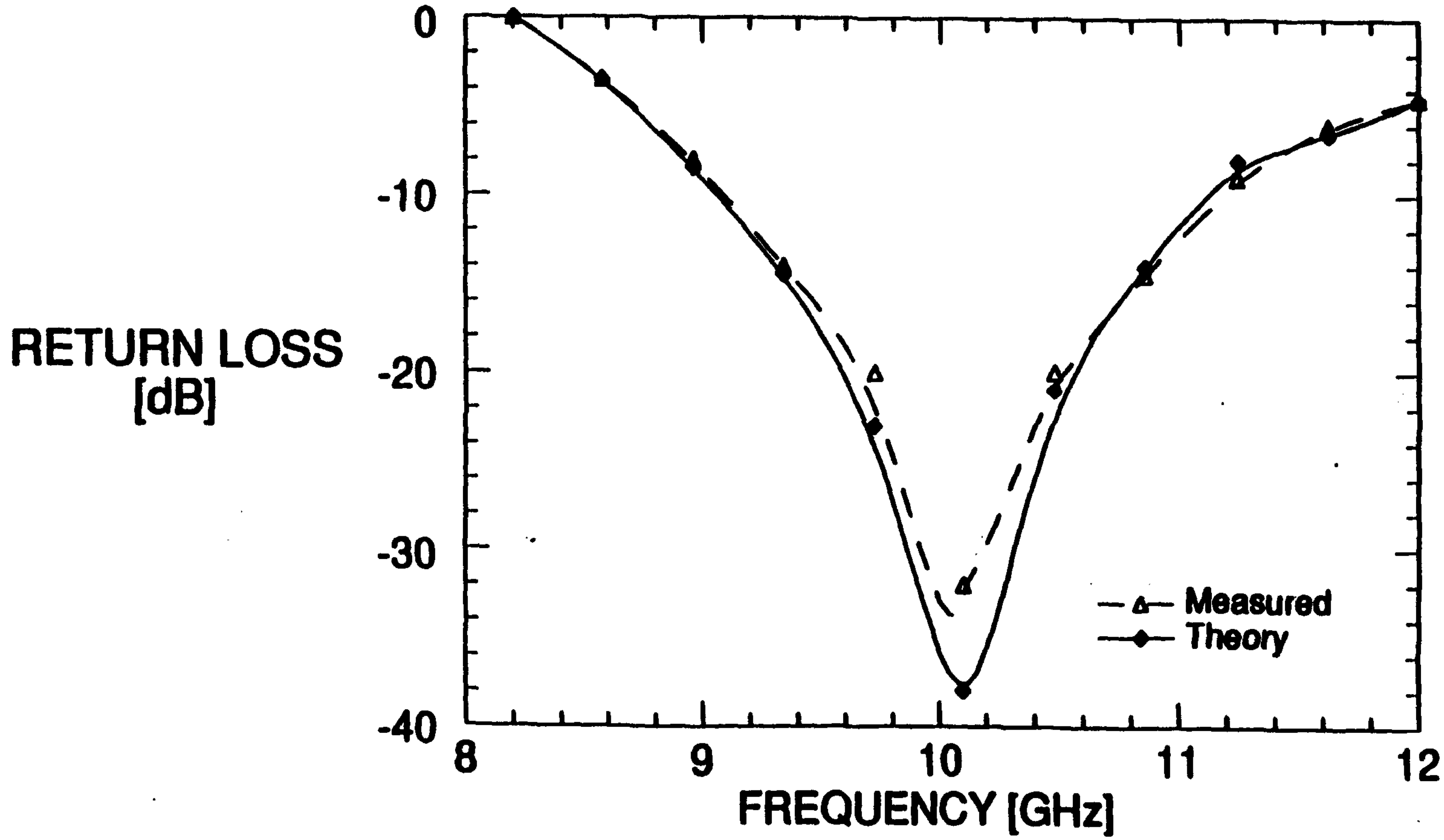

Design Features

- Clean Conversion of TE10 rect. into TM01 cyl. Mode
- Wide Instantaneous Bandwidth (>20%)
- Low Insertion loss (<1/10 dB at 10.1GHz Frequency Optimum)
- Tuneable Frequency Optimum

Frequency Optimum Tuning

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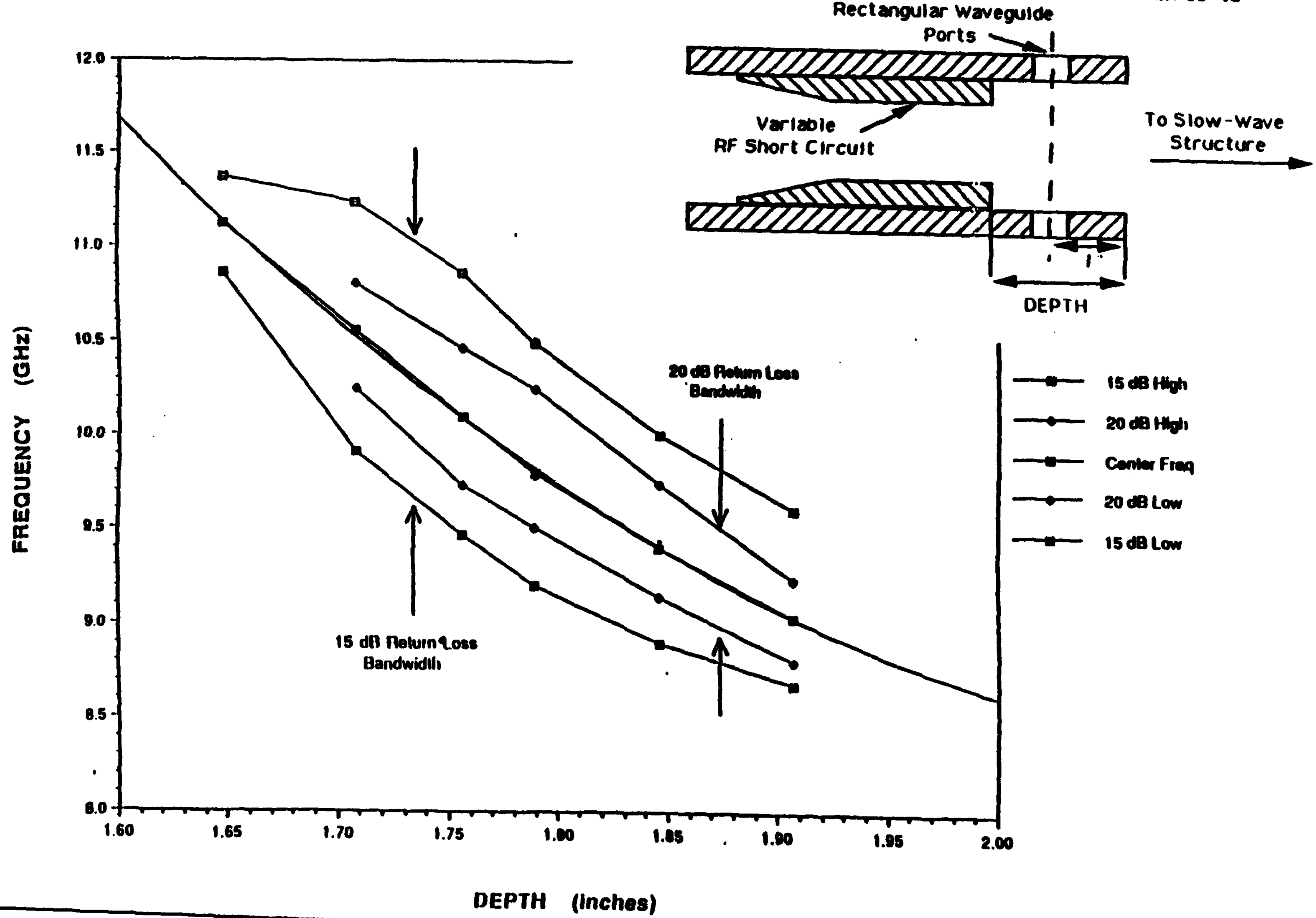

Klystron Performance

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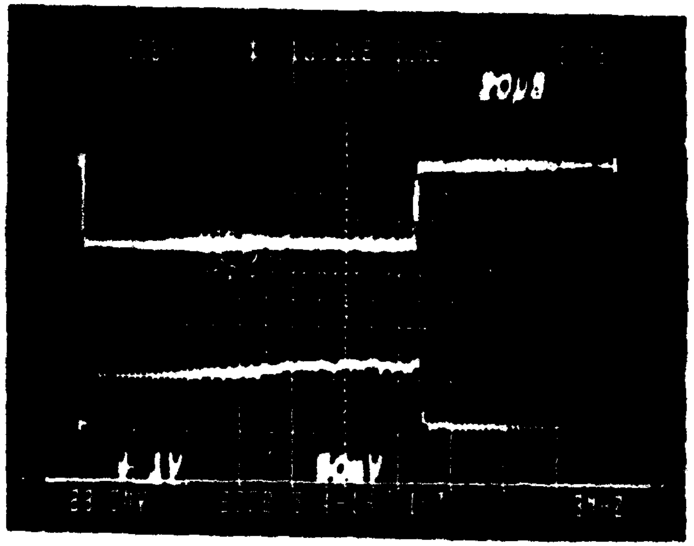
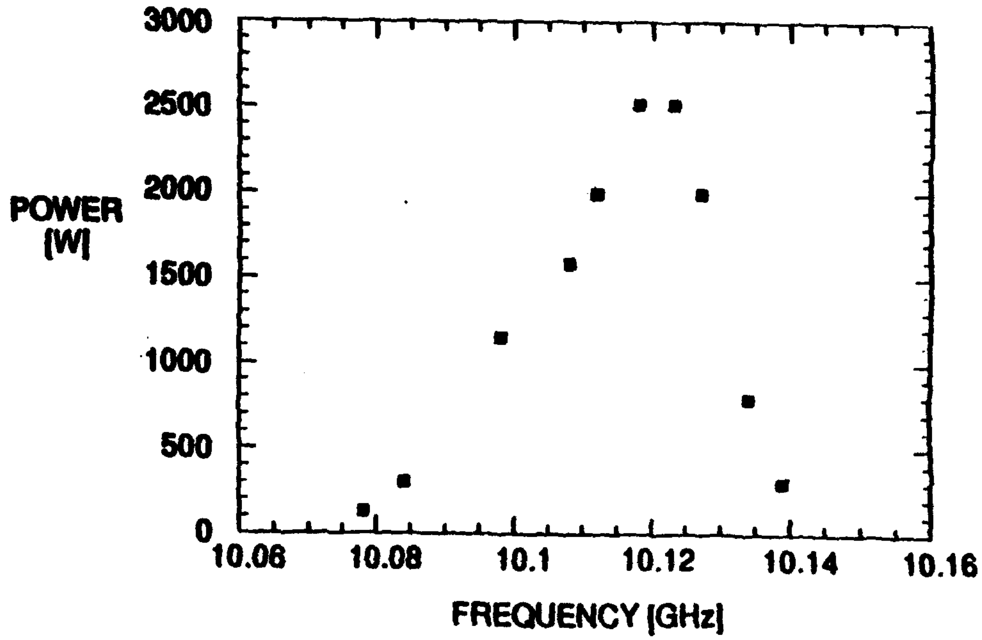
Calibrated Detector Er#1

Spectrum Analyzer 3MHz BW



20 µsec/div



Bandwdith 3 dB points 30 MHz

Typical X-Band Amplifier Operation

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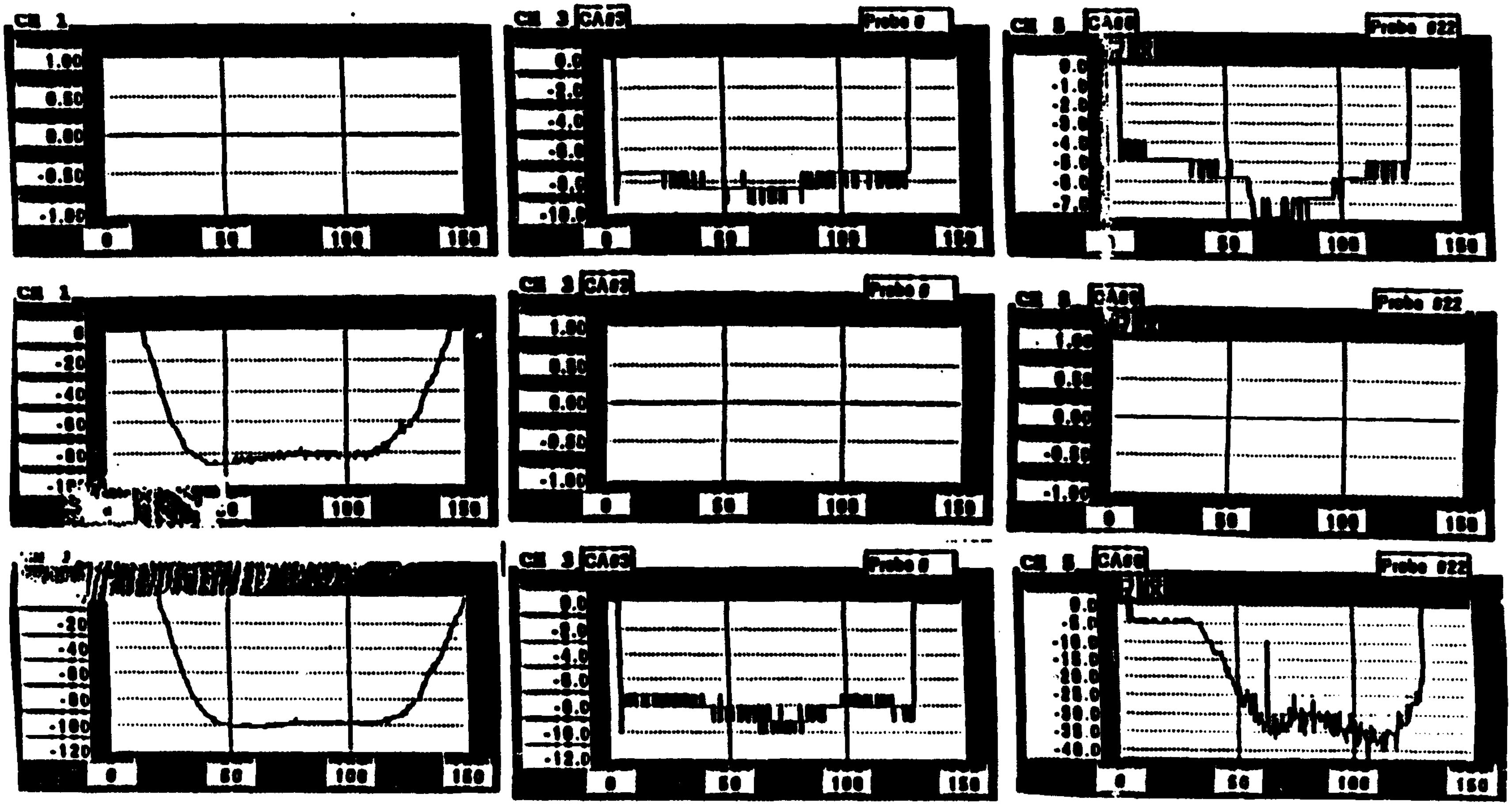
Current [A] | Input RF-10.1 GHz | Output RF

No Beam

No RF



GAIN ~ 10.7 dB

Amplifier Gain Versus Beam Voltage

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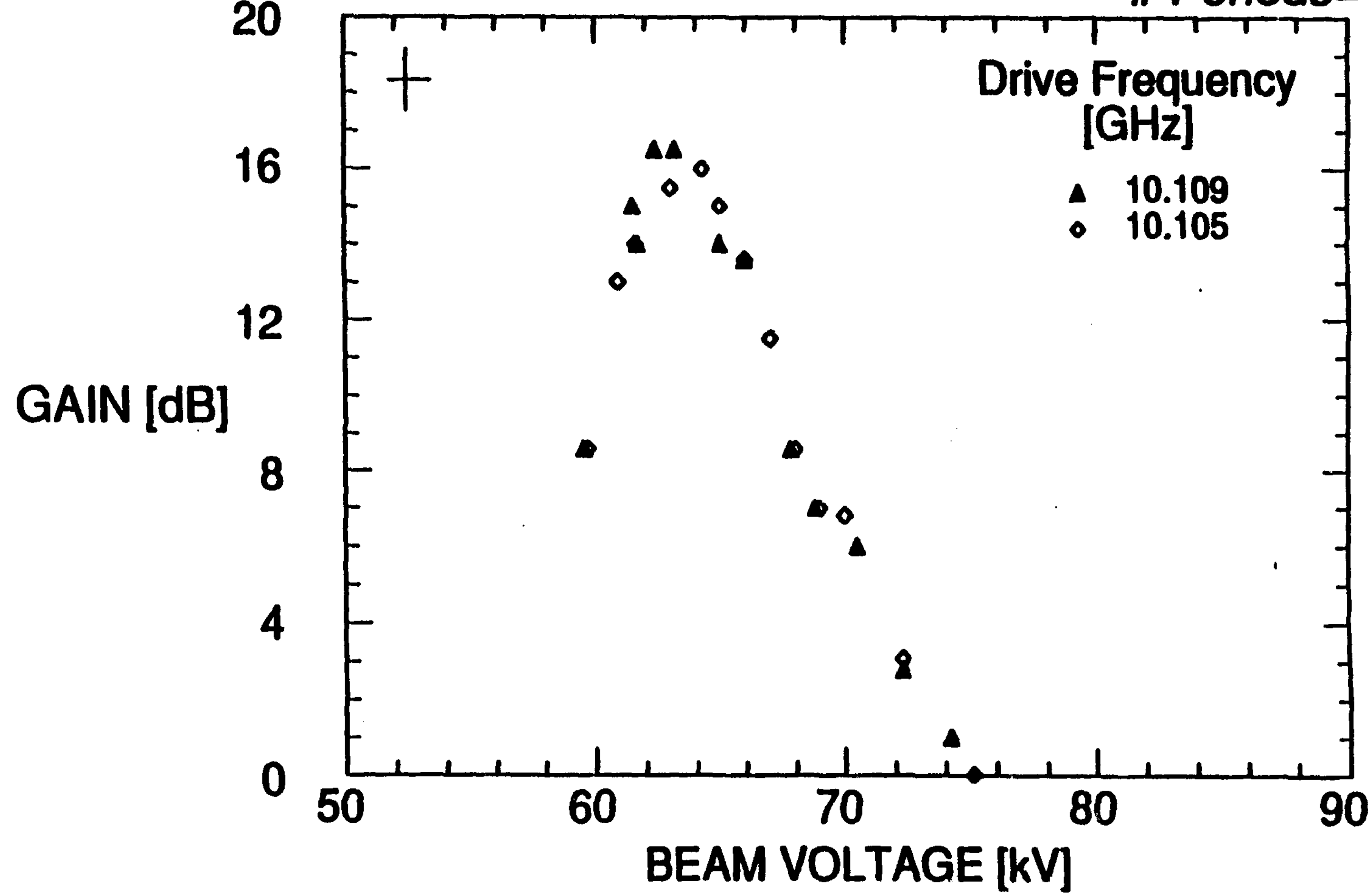
Beam Current=100 A
Xe Pressure=3.0x10-5Torr
Periods= 33



Gain Determined by Monitoring Downstream Er Probe with and without the e-beam

Gain Versus Beam Voltage as a Function of SWS Length

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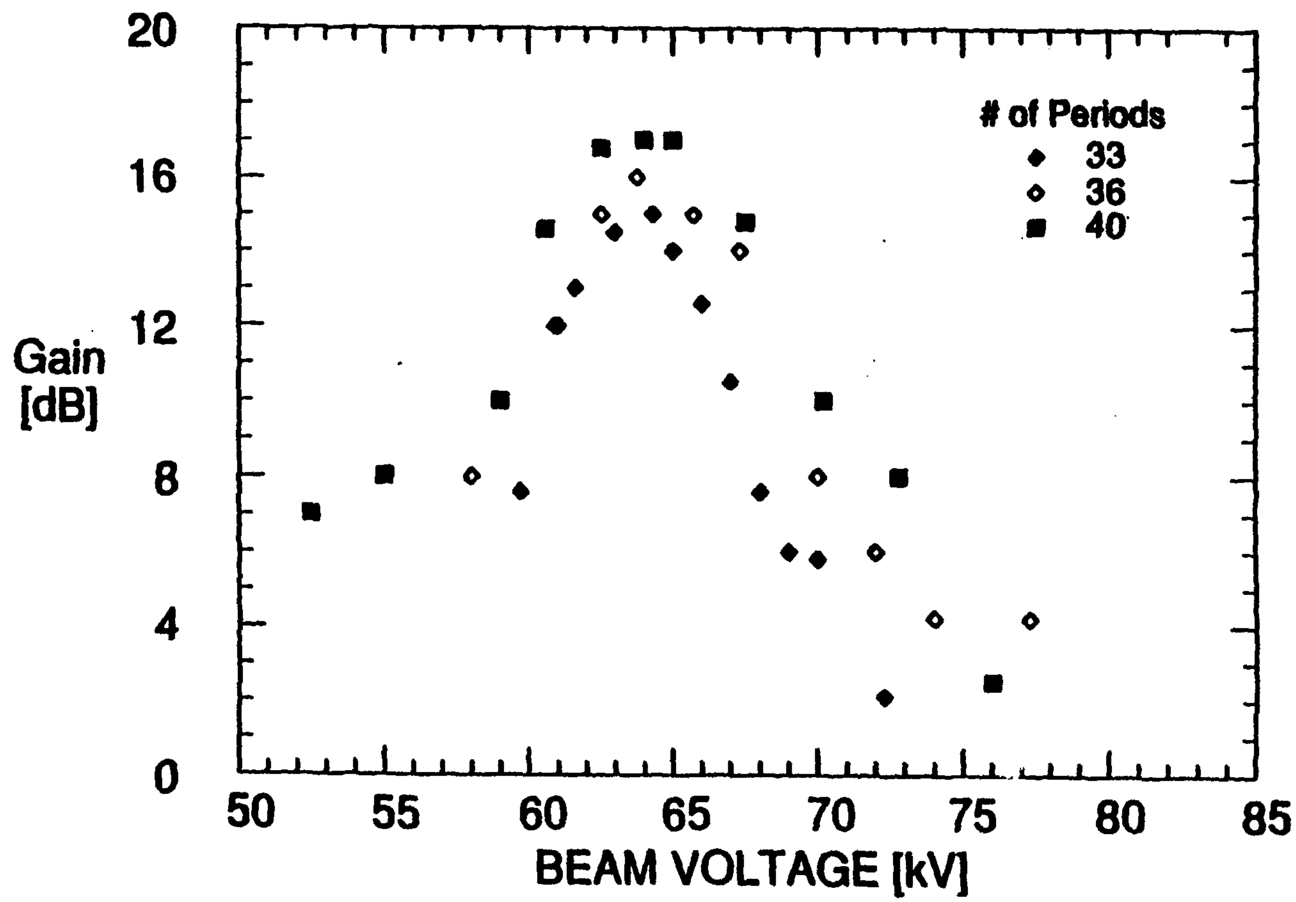
Beam Current=100 A
Xe Pressure=3.0x10-5Torr



Amplifier Gain Versus SWS Length

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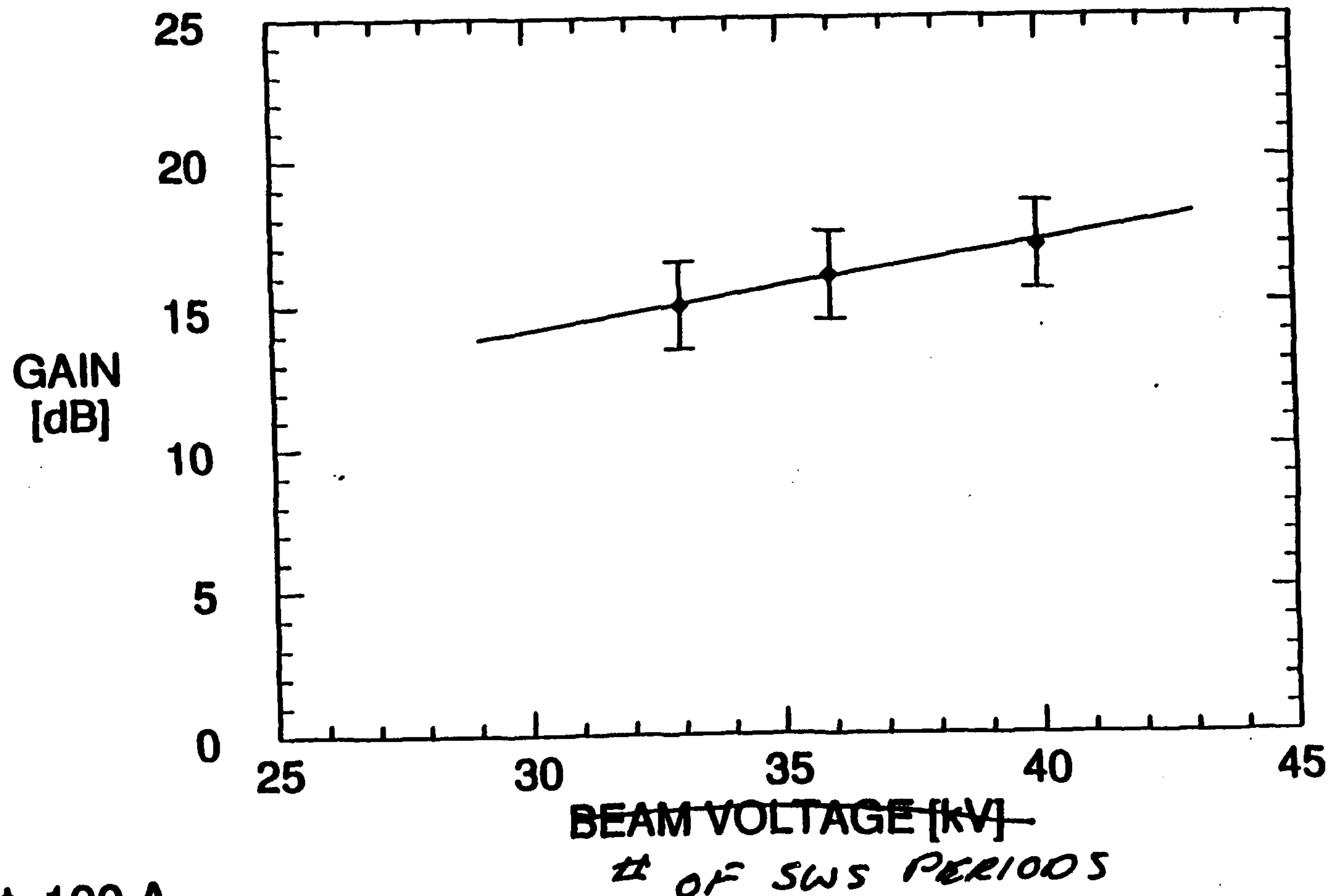

Beam Current=100 A
Beam Voltage= 63 kV
Drive frequency=10.109GHz
Xe Pressure=3.0x10-5Torr

Amplifier Efficiency Versus Beam Voltage

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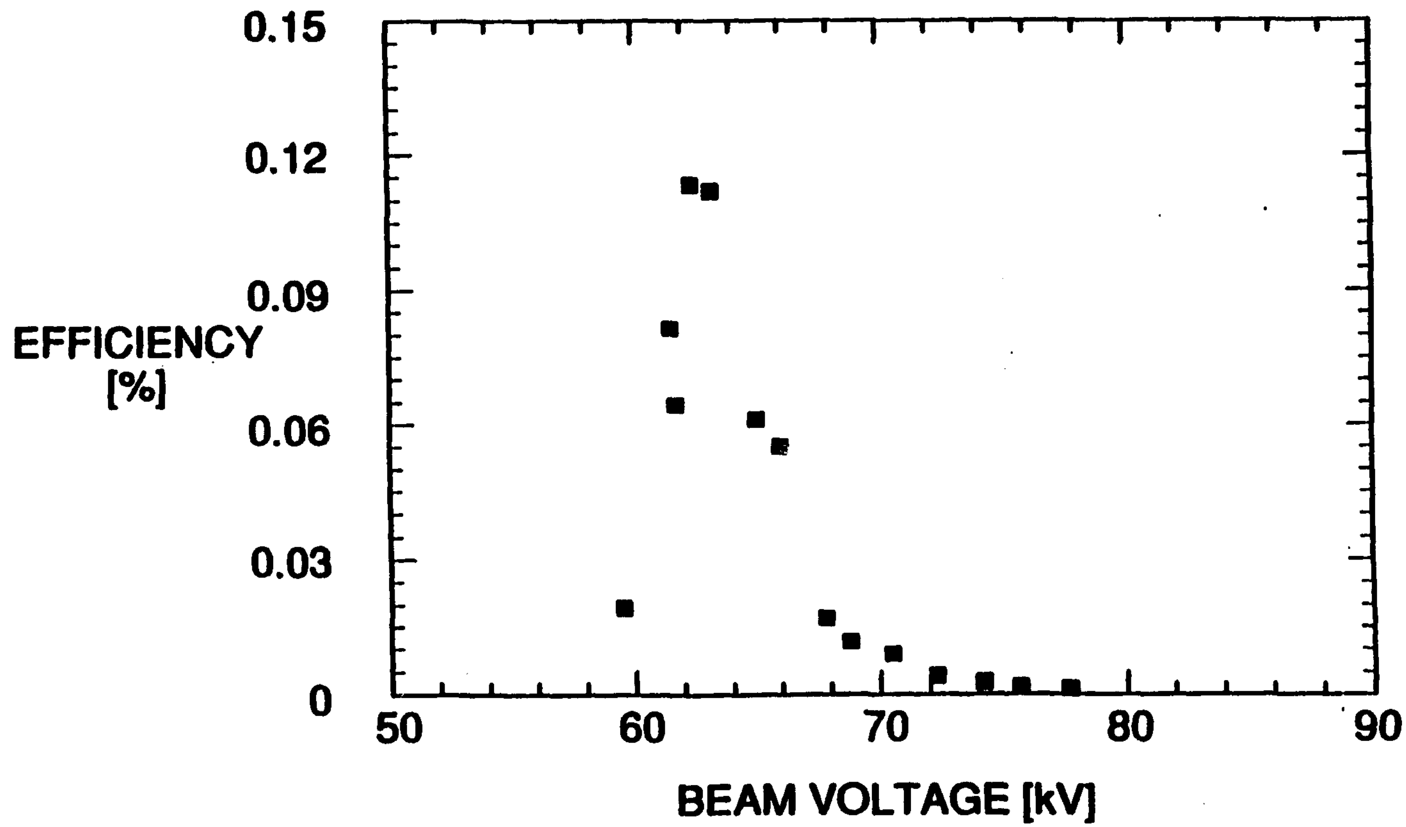
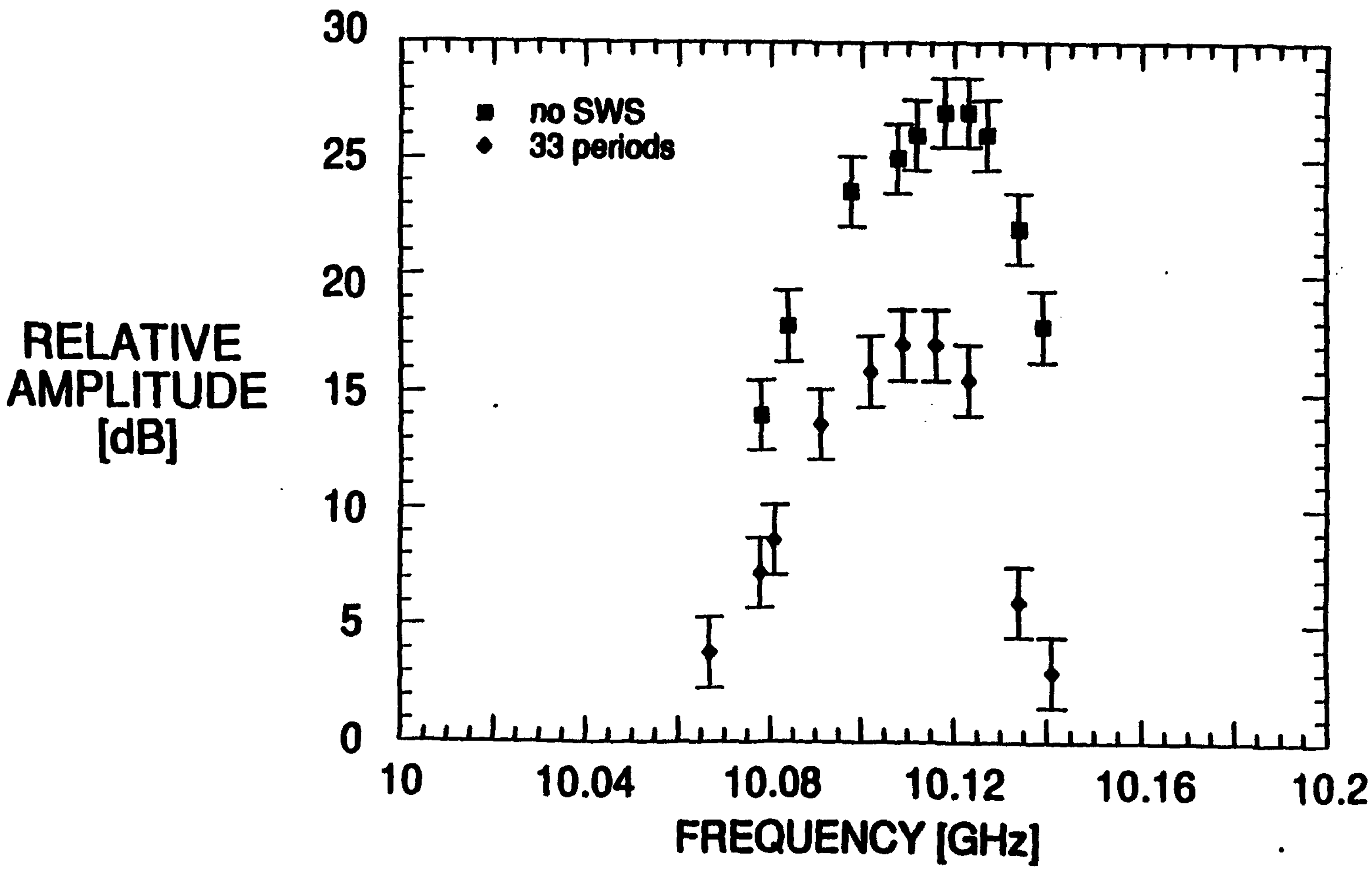
Beam Current=100 A
Xe Pressure=3.0x10-5Torr
Drive Frequency=10.109 GHz
Periods=33



High Measured Gain and Low Efficiency Due to Operation of the Amplifier Near Cut-off

Insertion Loss of SWS



Presence of SWS Dramatically Attenuates Rf Drive Signal

Gain Versus Rf Drive Frequency

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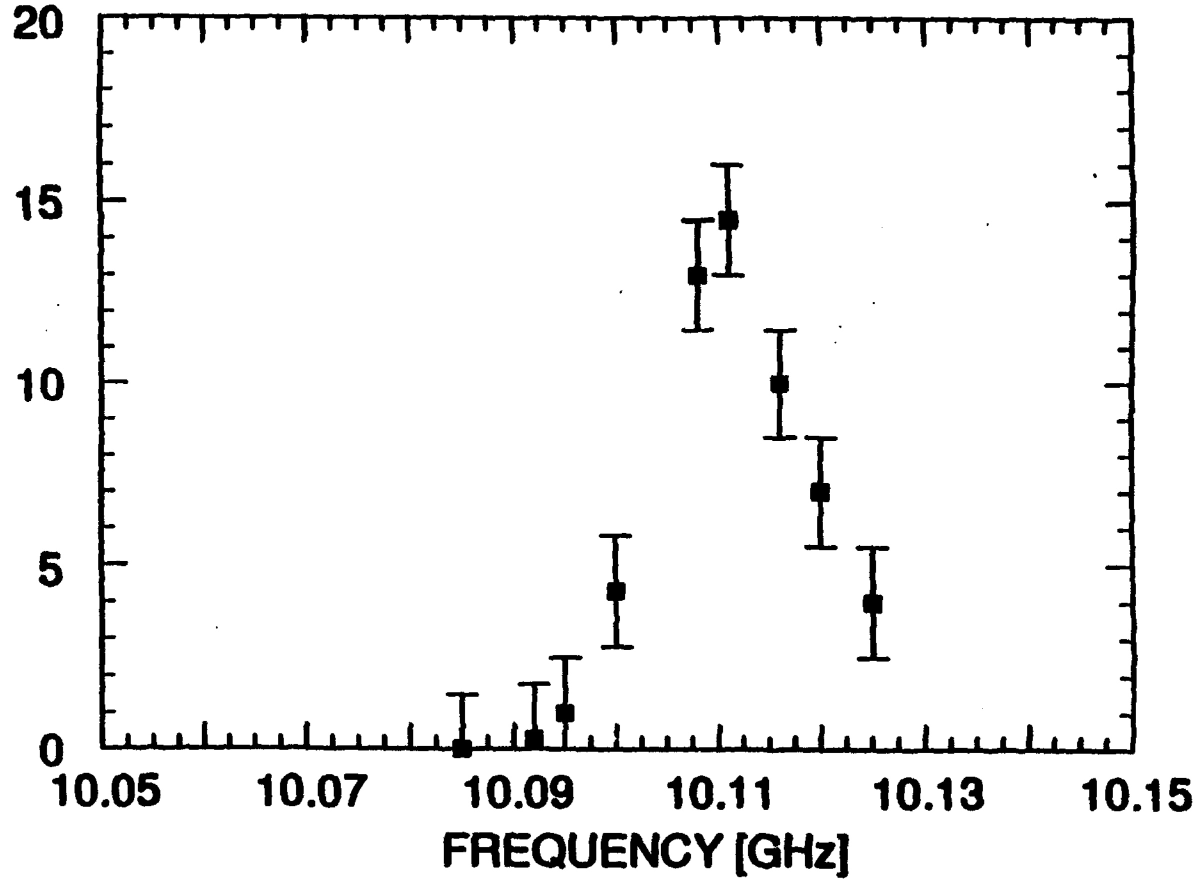
Beam Current=100 A
Beam Voltage= 63 kV
Xe Pressure=3.0x10-5Torr
Periods=33

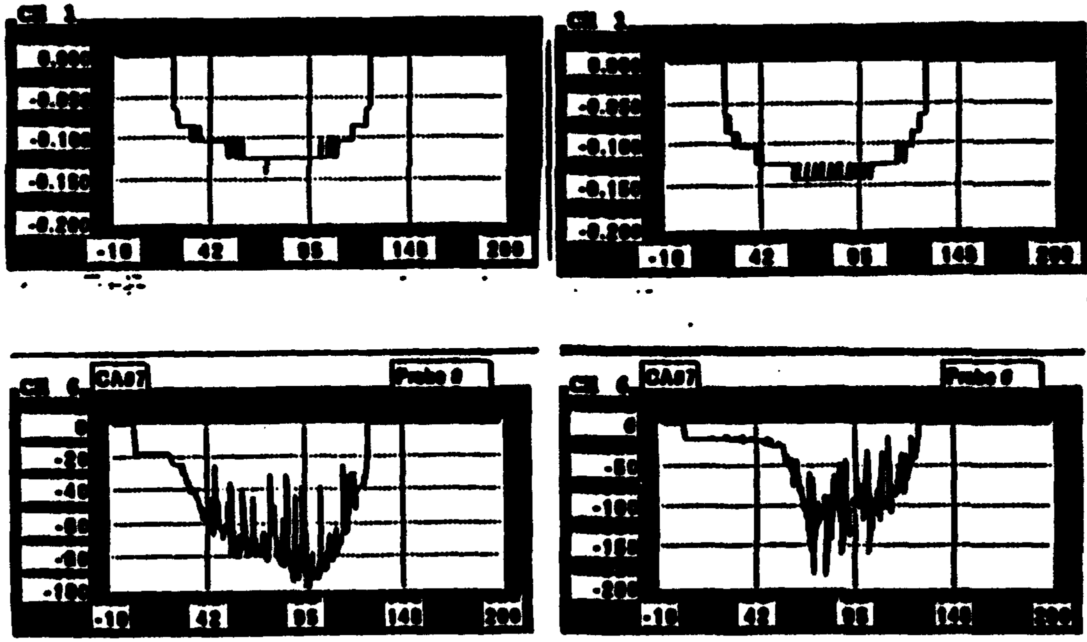


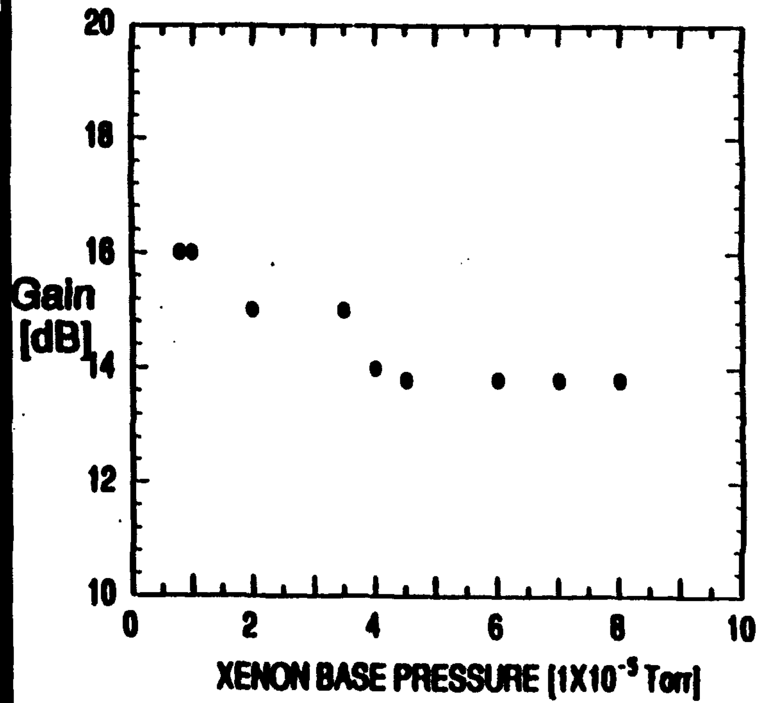
Influence of Background Gas Pressure on Amplifier Performance

HUGHES

JB-June 93- 27

Xe=3x10^-5 Xe=.8x10^-5





Traces show a reduction in RF turn on time as background gas pressure is increased
This effect is due to the increased ionization rate and thus focusing of the IFR beam.

Results/Plans

HUGHES

Results

Parameter	Goals	Demonstrate
RF Drive Source 1		
Center Frequency	10.1 GHz	10.12 GHz
Bandwidth	40 MHz	40 MHz
Peak Power	3.0 kW	2.7 kW
Pulsewidth	120 μsec	120 μsec
PASOTRON Amplifier		
Beam Voltage	50-100 kV	50-100 kV
Beam Current	50-150 A	80-120 A
Gain	10-30 dB	0-17 dB
Power	3 MW	7 kW
Efficiency	20-30%	0.1%
Bandwidth	>10%	0.1%
Pulsewidth	100 μsec	80 μsec

Plans

- Upgrade Amplifier RF Drive Source (Hughes 10 KW TWT)
- Investigate Amplifier Performance Away from Cut-Off Conditions (Lower Frequency and Higher Beam Voltage)
- Measure Phase Coherence with Anaren Phase Discriminator